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Instantaneous mitral valve leaflet velocity and its relation to left ventricular wall movement in normal subjects

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Echocardiograms showing mitral valve leaflets, interventricular septum, and posterior wall of the left ventricle simultaneously were recorded at a paper speed of 100 mm/s in 20 normal subjects. These records were manually digitized and a computer was used to derive mitral valve velocity, left ventricular dimension, and its rate of change continuously throughout a single cardiac cycle.

The pattern of instantaneous mitral valve velocity with respect to time was similar in all subjects studied, showing a peak opening rate of 400 $\pm$ 60mm/s (mean $\pm$1 SD), and continuously changing velocity throughout the period of mid-diastolic closure. The peak diastolic closure rate was 250 $\pm$ 60 mm/s and thus appreciably higher than average velocities obtained by manually measuring the slope.

A close time relation existed between mitral valve and left ventricular wall movement in early diastole. Forward movement of the anterior leaflet began 1 $\pm$ 6 ms after the onset of outward wall movement, and peak velocity was reached 2 $\pm$ 7 ms after the maximum rate of change of dimension. Later, a discontinuity in wall movement at the end of rapid filling preceded a corresponding discontinuity in the mitral valve velocity tracing by 5 $\pm$ 10 ms.

The technique, therefore, allows continuous measurement of mitral valve velocity, and demonstrates its close relation to left ventricular wall movement during diastole.

The diastolic closure rate of the anterior leaflet of the mitral valve is a fundamental measurement in echocardiography, and a number of disturbances of left ventricular function have been diagnosed on the basis of values lying outside the normal range (Feigenbaum, 1972). Initially, these measurements were made on the assumption that the velocity of valve movement was uniform throughout the period of mid-diastolic closure but more recently, biphasic (Quinones *et al.*, 1974; Madeira *et al.*, 1974) and intermediate (Rodger and Sumner, 1975) patterns have been described. In view of the physiological significance attributed to abnormalities of mitral valve movement and the diversity of means by which the measurements were made, we have modified traditional methods of study by recording echocardiograms at a paper speed of 100 mm/s and digitizing them manually to derive anterior leaflet velocity continuously throughout the cardiac cycle. This has permitted us to study the pattern of mitral valve movement in greater detail than was possible with previous methods and to compare its time relations with those of the left ventricular wall during ventricular filling.

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Subjects and Methods

Subjects

Echocardiographic studies were performed on 20 normal volunteers in a resting state. Their ages ranged from 16 to 59, and 13 were men. All were in sinus rhythm and none had a previous history of heart disease.

Echocardiographic methods

All measurements were made with an Ekoline 20 ultrasonoscope (frequency 2·25 MHz, repetition frequency 1000/s). The output was displayed on a Cambridge multichannel strip chart recorder at a paper speed of 100 mm/s, with a simultaneous electrocardiogram. The subjects were studied in the supine or slightly left lateral position with the transducer at the left sternal border in the 3rd, 4th, or 5th interspace. The transducer was angled down from the aortic root through the mitral ring until echoes were obtained simultaneously from the septum, posterior wall, and the anterior leaflet of the mitral valve (Fig. 1). Measurements were only made on those recordings showing clear, continuous endocardial echoes from the septum and the posterior wall, and, in addition, the posterior mitral leaflet had to be recorded at least part of the time during diastole before the record was accepted for measurement.

Digitizing methods

Echocardiograms were digitized as previously described (Gibson and Brown, 1973), tracing echoes of the septum, posterior wall, anterior leaflet, and whenever possible, posterior leaflet, on a DMAC digitizing table interfaced with the IBM 1800 computer at Westminster Hospital. Strings of co-ordinates were generated for approximately 100 points on each of these echoes together with calibration signals representing 0·5 s, 1 cm, and the RR interval of the beat being studied.

Analysis of data

From the digitized data, plots were made of the positions of wall and leaflet echoes, instantaneous leaflet velocities, left ventricular dimension (D), rate of change of dimension (dD/dt), and normalized rate of change of dimension (1/D·dD/dt) (Fig. 2). Peak velocities of leaflet movement during early diastolic opening (D-E), mid-diastolic closure (E-F), atrial systolic opening (F-A), and end-diastolic closure (A-C) were measured directly. The times to peak opening and mid-diastolic closing velocities were measured directly and the corresponding accelerations derived as the mean slope of the velocity curve over the two intervals from the D and E points, respectively. In addition, the time relation between wall and mitral valve movement was analysed by measurement of the intervals between the time of 1) the onset of outward wall movement and that of the valve, 2) the peak rate of change of dimension and peak opening velocity of the valve, and 3) a discontinuity in the rate of wall movement and a corresponding one in the velocity tracing during mid-diastolic closure.

Critique of Methods

1) Measurement of position

All measurements of position of single echoes were made relative to the anterior chest wall. This does not affect estimates of left ventricular cavity size which was calculated as the distance between septal and posterior wall echoes and was thus independent of transducer position. Measurements of anterior leaflet velocity however, when made relative to any fixed external reference point, include a component caused by movement of the mitral ring (Zaky, Grabhorn, and Feigenbaum, 1967). In order to estimate the contribution of the latter, mitral ring echoes were recorded in 5 subjects and its velocity derived using the same methods as for the valve. Peak mitral ring velocities were small (less than 100 mm/s) and always occurred before those of the valve leaflets (Fig. 3). It appears, therefore, that measurement of the pattern of valve movement during diastole is not significantly distorted by use of the anterior chest wall as a reference point.

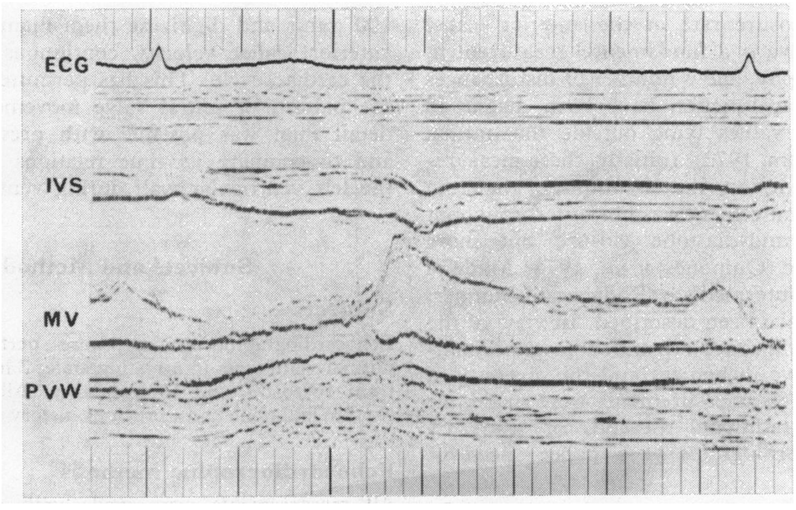

FIG. 1 *Echocardiogram recorded with a strip chart recorder at 100 mm/s showing interventricular septum (IVS), posterior left ventricular wall (PVW), and mitral valve (MV), with a simultaneous electrocardiogram (ECG).*

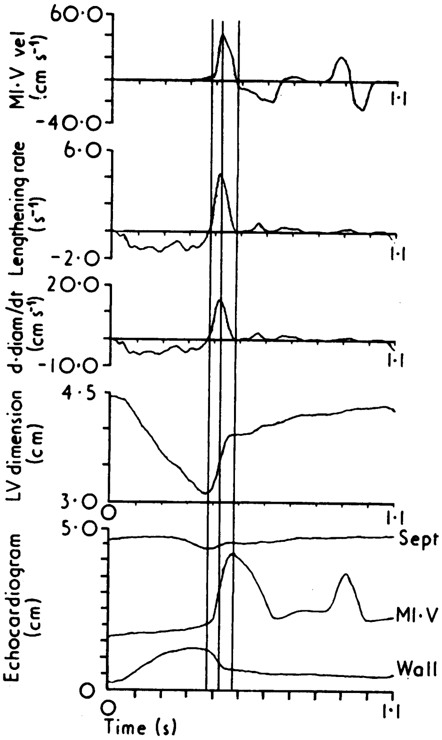

FIG. 2 *Computer output of digitized mitral valve and cavity echoes showing, from below, direct printout of echoes, left ventricular dimension, rate of change of dimension, normalized rate of change of dimension, and (top) instantaneous anterior mitral leaflet velocity. Vertical lines demonstrate: 1) onset of outward wall movement and anterior leaflet movement; 2) peak rate of wall and leaflet movement; and 3) discontinuity in wall movement and leaflet velocity during mid-diastolic closure.*

2) Technique of recording

Anterior mitral leaflet velocities were only measured from records which also showed echoes from the septum, the posterior wall, and at least part of the posterior leaflet. In order to compare measurements made in this position with those in which the ultrasound beam passed through the free edge of the leaflet, sweeps were made in 5 subjects of the mitral leaflet from the aortic root to its insertion into the papillary muscle. Derived velocities from successive beats were superimposed after being lined up on their respective QRS complexes (Fig. 4). It is apparent that estimates of peak velocity and the times to these peaks, vary little with position along the valve except that records derived from close to the aortic root show a pattern of movement intermediate between that of leaflet and ring.

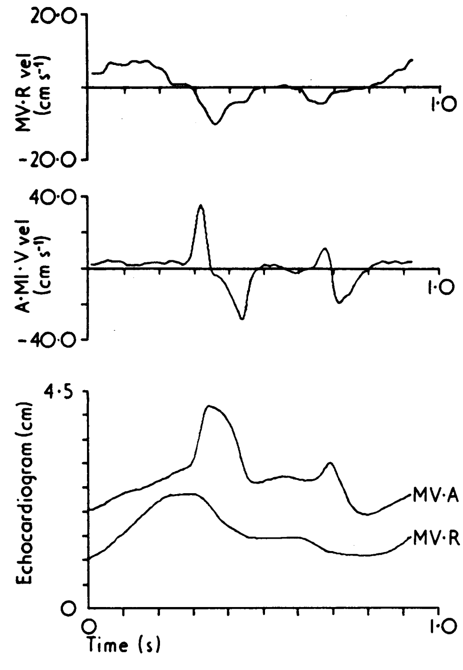

FIG. 3 *Computer output of digitized echoes from mitral valve and ring showing, from below, direct printout of echoes of ring (MVR) and anterior leaflet (MVA), instantaneous anterior leaflet velocity, and (top) instantaneous mitral ring velocity. Peak mitral ring velocity is less than leaflet velocity in diastole, and occurs earlier.*

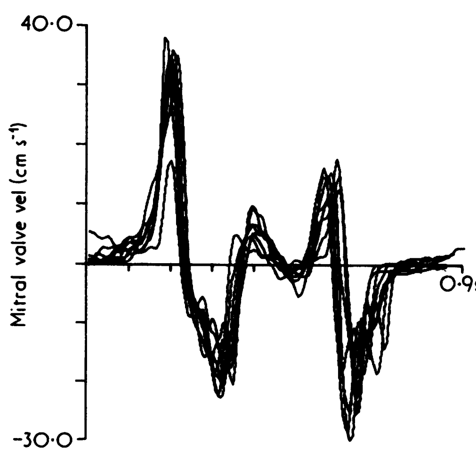

FIG. 4 *Eight superimposed velocity traces from the anterior leaflet in a single subject, obtained during a sweep from aortic root to mitral leaflet insertion into the papillary muscle.*

3) Relation of mitral leaflet movement to valve opening

In the present technique, the onset of forward movement of the anterior leaflet rather than actual valve opening is measured. Recent studies suggest that there is no direct relation between these two events and that valve opening may occur slightly later than the separation of the valve leaflets on the echocardiogram (Pohost *et al.,* 1975; Rubenstein *et al.,* 1975). Though the exact timing of mitral valve opening rather than the onset of forward movement of the anterior leaflet is not relevant to the present study, these observations are in line with angiographic data demonstrating outward wall movement before the appearance of unopacified blood from the left atrium within the left ventricular cavity (Prewitt *et al.,* 1975a).

4) Reproducibility

In 10 subjects, 2 successive beats were analysed by the same observer and reproducibility estimated as the root mean square difference between duplicate determinations. For paired velocities, these were 26 mm/s for early diastolic opening (D-E), 22 mm/s for mid-diastolic closure (E-F), 13 mm/s for atrial systolic opening (F-A), and 35 mm/s for end-diastolic closure (A-C); and for paired events of mitral valve and wall movement: 2·2 ms for the onset, 2·6 ms for the peak, and 3·7 ms for the discontinuity of movement.

5) Frequency response

The frequency response of the echocardiograph and digitizing system has previously been investigated in detail and found to be entirely adequate to study mitral valve and wall movement without distortion (Gibson and Brown, 1973).

Results

Mitral valve movement

A characteristic pattern of mitral valve movement was found in all 20 normal subjects studied (Fig. 5). After the onset of forward movement (D point), the velocity of the anterior leaflet increased until an early peak was reached and then returned rapidly to the baseline by the time of maximum excursion of the leaflet itself (E point). This same rapid rate of change of velocity persisted for a variable period during the early phase of mid-diastolic closure, but after an abrupt change in the slope of the curve, the rate of change increased more gradually until a late peak was reached. The curve then returned to the baseline by the time of maximum leaflet excursion in mid-diastole (F point). At no time was a constant velocity recorded during mid-diastolic closure, which would have resulted in one or more horizontal segments in the velocity

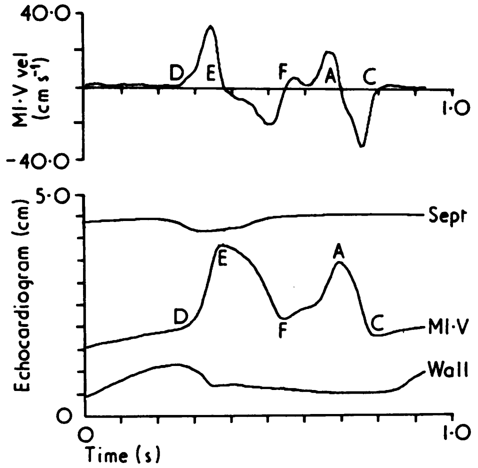

FIG. 5 *Computer output of digitized mitral valve echo (anterior leaflet), with its instantaneous velocity above.*

tracing. Instead, early diastolic movement could be described in terms of four periods of nearly constant rate of change of velocity, i.e. of nearly constant acceleration. The first was from the onset of anterior movement of the leaflet to peak opening rate, the second from peak opening rate to the abrupt change in slope early during mid-diastolic closure, the third from this time until peak closure rate, and the fourth ending with the F point.

Similar deflections were found in the velocity tracing during atrial systolic opening and end-diastolic closure. The velocity curve of the posterior leaflet was virtually a mirror image of that of the anterior (Fig. 6).

Peak velocities

The mean value for the peak opening velocity of the anterior leaflet was 400 $\pm$ 60 mm/s and it occurred 60 $\pm$ 10 ms after the onset of forward movement (D point). The peak closing velocity was 250 $\pm$ 60 mm/s, occurring 100 $\pm$ 20 ms after the onset of mid-diastolic closure (E point). Thus, the mean slope during opening corresponded to an acceleration of 0·67 $\pm$ 0·15 *g*, and during mid-diastolic closure to an acceleration of −0·27 $\pm$ 0·08 *g*. The peak velocity during atrial systole was 250 $\pm$ 70 mm/s and during end-diastolic closure was 290 $\pm$ 80 mm/s.

In 5 patients in whom it was possible to record posterior leaflet velocities, the peaks were: 190 $\pm$ 40 mm/s for opening, 90 $\pm$ 10 mm/s for mid-diastolic closure, 110 $\pm$ 30 mm/s for atrial systolic opening, and 120 $\pm$ 40 mm/s for end-diastolic closure.

Relation of wall to mitral valve movement

In early diastole, there was a close time relation between left ventricular wall and anterior leaflet movement (Fig. 2). The onset of forward movement of the anterior leaflet followed that of outward wall movement by 1 $\pm$ 6 ms; the peak opening velocity followed peak rate of wall movement by 2 $\pm$ 7 ms, and later a discontinuity in the rate of wall movement preceded a similar discontinuity in mitral movement during mid-diastolic closure by 5 $\pm$ 10 ms. These corresponding events of wall and mitral valve movement were simultaneous as best we could determine, since the time intervals did not differ significantly from zero.

After the cusps separated, the posterior leaflet reached its peak opening velocity 20 $\pm$ 10 ms before that of the anterior leaflet, and the discontinuity during mid-diastolic closure also occurred 20 $\pm$ 10 ms earlier (Fig. 6).

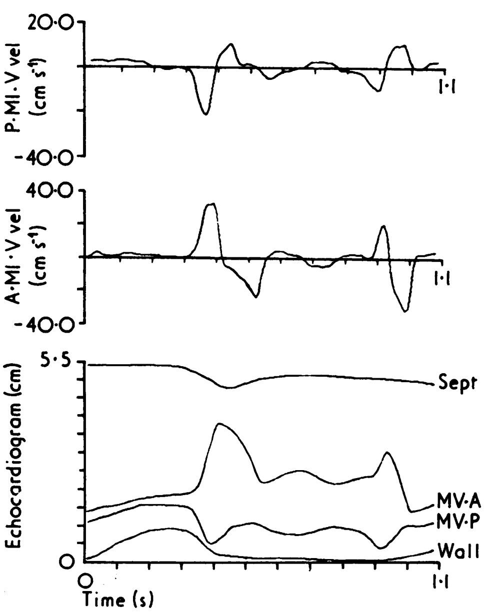

FIG. 6 *Computer output of anterior and posterior mitral leaflet echoes showing, from below, direct printout of echoes from posterior wall, posterior cusp (MVP), anterior cusp (MVA), and septum. Above are shown instantaneous velocities of anterior and (top) posterior cusps.*

Discussion

The rate of descent of the anterior mitral valve leaflet in mid-diastole was first noted to be diminished in mitral stenosis and the practice of measuring the diastolic closure rate was introduced to diagnose and quantify the severity of the disease (Edler, 1955; Effert, Erkens, and Grosse-Brokhoff, 1957; Gässler and Samlert, 1958). Since differences between normal and rheumatic valves were great, they could readily be demonstrated by simple manual measurements from records made at slow sweep speeds. It soon became apparent however, that the diastolic closure rate could be outside the normal range in the absence of mitral valve disease, and both increased (Segal, Likoff, and Kingsley, 1967; Madeira *et al.*, 1974) and decreased (Shah *et al.*, 1968; Popp and Harrison, 1969; Duchak, Chang, and Feigenbaum, 1972) values have been reported. In these circumstances, however, there is a spectrum of values from the normal to the abnormal range, and it has been suggested that this variable may be related in some way to ventricular filling or compliance (Zaky, Nasser, and Feigenbaum, 1968; Quinones *et al.*, 1974). Since these ideas have potential clinical significance, the need to determine diastolic closure rate unambiguously becomes apparent. These measurements are technically easy to make in mitral stenosis since the closure rate is constant throughout the greater part of diastole, but when the leaflet echo is normal, our results have shown that closure rate increases throughout the early diastolic filling period, so that the segment to be measured is curved. If a slow sweep speed is used to record the echogram, this curve is not apparent (Fig. 7) and manual estimation results in the mean rather than the peak value of the slope between the E and F points. If a faster sweep speed is used, then a tangent must be constructed whose slope is to some extent arbitrary. It is not surprising, therefore, that a wide range of values has been recorded for the normal diastolic closure rate, diminishing the specificity of this variable (Table). It is unlikely that this scatter is caused by any differences in the populations of normal subjects studied but rather it seems to reflect lack of uniformity in methods of recording and analysing the echocardiograms.

In order to resolve these difficulties, we have recorded mitral valve echograms at a fast paper speed using a strip chart recorder and have used a digitizing technique to derive velocity continuously throughout the cardiac cycle. Measurements of diastolic closure rate made in this way cannot be compared directly with others already published,

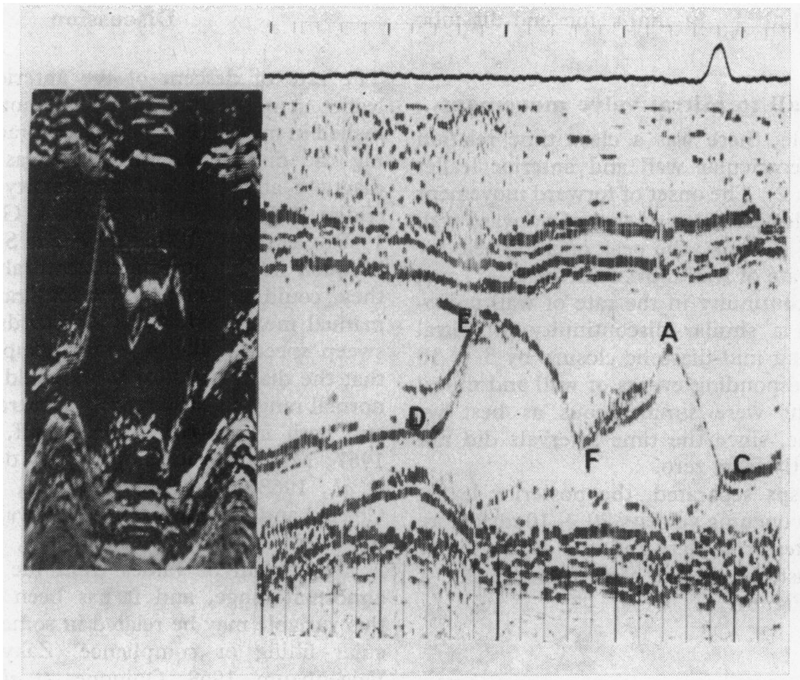

FIG. 7 *Echograms of the mitral valve recorded in the same subject on Polaroid film (left) and a strip chart recorder at 100 mm/s (right). It is apparent from the record on the right that the velocity of closure is not constant during mid-diastole but this is not obvious on the record on the left, taken at a lower sweep speed.*

since we have derived peak rather than mean values, so that the figure of 250 ± 60 mm/s for that of the anterior leaflet is considerably higher than previously reported in normal subjects (Table).

TABLE *Values reported for the normal diastolic closure rate*

Study	*Year*	*Range (and mean) (mm/s)*
Edler and Gustafson	1957	85–150 (120)
Effert	1959	86–200 (125)
Joyner, Reid, and Bond	1963	85–160
Segal *et al.*	1967	70–150
Winters *et al.*	1969	65–210
Popp and Harrison	1969	80–150
Pridie, Benham, and Oakley	1971	70–120
Ross	1972	70–160 (114)
Layton *et al.*	1973	58–139 (92)
Quinones *et al.*	1974	60–110 (85)
Madeira *et al.*	1974	115–225 (173)
Rodger and Sumner	1975	128–234 (176)

Measurements of posterior leaflet velocity were also made and shown to be approximately half the corresponding values for the anterior leaflet, with a peak diastolic closure rate of 90 ± 10 mm/s. The mitral ring contributed little to mitral valve movement during diastole, since its peak velocity was considerably lower and occurred earlier than that of either anterior or posterior leaflet.

The use of continuous digitization also allowed the pattern of mitral valve movement to be investigated. The form was similar in all normal subjects and showed a series of periods of relatively constant acceleration, resulting in continuously changing velocity. The time intervals over which these accelerations appeared to operate were not necessarily synchronous with valve position. For example, the rapid deceleration at the end of early diastolic opening of the leaflets frequently persisted beyond the time of maximum opening and so caused a brief rapid acceleration at the onset of mid-diastolic closure.

Since the normal mitral leaflets are thin and pliable, acceleration and deceleration of blood into the ventricle seems to provide the force necessary for mitral valve movement. This idea is not new since in 1837, Mcartney *et al.* suggested that mid-diastolic closure might occur, and 6 years later, Baumgarten (1843) clearly showed this event in association with deceleration of flow into the isolated left ventricle. More recently, the presence of vortices behind the valve leaflets has been demonstrated experimentally (Henderson and Johnson, 1912; Brockman, 1966; Bellhouse, 1972) while Laniado *et al.* (1975) in dogs have shown close correlation between transmitral blood flow and valve movement. Our results are compatible with these observations. The virtually simultaneous onset of mitral valve and outward wall movement and the close relation between the two during early diastole suggest that the forces acting on the valve are closely related to the pattern of ventricular filling. If valve movement is assumed to obey simple Newtonian mechanics, the application of a constant force would result in a period of constant acceleration. Our results suggest that during early diastole, valve movement can be described in such terms, with the initial three periods of acceleration each apparently corresponding to a well-defined phase of ventricular filling. The first phase of acceleration terminates with peak opening rate which is synchronous with the peak rate of wall movement and therefore with the 'O' point of the apex cardiogram (Prewitt *et al.*, 1975b) and the nadir of the ventricular pressure trace (Willems, de Geest, and Kesteloot, 1971). This initial period of filling, when ventricular volume increases as pressure is still falling, is one which departs widely from any simple passive model (Dodge, Hay, and Sandler, 1962). The second period of valve movement extends from peak opening rate to the discontinuity on the velocity trace during mid-diastolic closure. This occurs at the same time as a corresponding discontinuity on the dimension record, noted as long ago as 1910 by Straub and more recently shown to correspond, in many cases, with the third heart sound (Prewitt *et al.*, 1975b). Finally, the period of lesser acceleration which terminates with peak closure rate is associated with a greatly reduced rate of outward wall movement. The fourth period, ending when the leaflet reaches the closed position, does not correspond to any feature of wall movement, so that the constraint on the valve may be the result of some other factor such as a restraining force developed by the subvalve apparatus.

In contrast to early diastolic events, atrial systolic opening and presystolic closure were not accompanied by significant wall movement. The reason for this is not clear from our observations but may have been the result either of a different mechanism of valve closure during atrial systole, or of failure of changes in left ventricular diameter to reflect filling in late diastole. In favour of the latter explanation are the observations of Laniado *et al.* (1975) in the dog, who demonstrated atrial systolic opening to be accompanied by a significant increase in transmitral flow. Further evidence in man comes from lower estimates of left ventricular volume changes during atrial systole made by echocardiography (Gibson and Brown, 1973) in comparison with those derived from angiocardiograms (Hammermeister and Warbasse, 1974), while the asymmetrical pattern of left ventricular filling at this stage of the cardiac cycle can be demonstrated angiographically, the increased volume being accommodated almost exclusively by prolongation of the long axis (Gibson and Brown, unpublished).

If the pattern of mitral valve movement is to be used as an index of ventricular filling in early diastole, it seems likely that continuous measurement of instantaneous velocity rather than estimation of mean values will reflect the rapidly changing determinants of blood flow into the left ventricle during this period. There is some evidence that comparison of mitral valve and wall movement may have practical significance since the close relation between the two provides an additional criterion of normality. Preliminary results suggest that this close relation may be lost when ventricular contraction is impaired and the normal filling pattern of the left ventricle disturbed (Upton, Gibson, and Brown, 1975).

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